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CARBON MONOXIDE AND CARBON DIOXIDE IN CLOSED-TYPE POWER TRANSFORMERS

SUMMARY

Gases carbon monoxide (CO) and carbon dioxide (CO_2) are formed in transformers in larger quantities as a product of degradation of cellulose, than by oxidation of oil.

In transformers with closed-type breathing system, without any indication of failure or fault, it was observed that the concentrations of CO are higher than the typical values according to IEC 60599 and CO_2/CO ratios lower than 3 frequently have been found.

This paper presents results of laboratory investigation of some influence parameters on formation gases CO and CO_2.

The typical values for CO as well scheme concerning their ratios need to be revised in standard IEC 60599. The criteria need to be established separately for closed type transformers.

Key words: carbon monoxide, carbon dioxide, cellulose, mineral oil

1. INTRODUCTION

Thermal and electrical overstresses in power transformers decompose insulating materials oil and paper and generate gases, which dissolve in the oil. Characteristic gases are: hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide (CO), carbon dioxide (CO_2). They are determined by the standardized laboratory method, gas chromatography analysis of the gases dissolved in oil [1]. Based on their quantity and ratio, the condition of transformer insulation system is estimated.

The gases carbon monoxide (CO) and carbon dioxide (CO_2) are formed in large amounts as a product of cellulose degradation processes, depending strongly on temperature, water and oxygen contents. The polymeric chains of cellulosic (paper) insulation are thermally less stable than the hydrocarbon bonds in oil, and are therefore decomposed at lower temperature.

Apart from that, carbon gases are formed in a transformer in lesser amounts as a product of oil degradation. In some cases carbon gases can be formed as a degradation product of some other organic materials (paints, rubber, plastic materials, glues etc.).

In transformers with closed-type breathing system oxygen content in oil is lower than in air saturated oil. It means that at the same temperature more carbon monoxide will be produced and concentration will grow faster than in oil in open-breathing system transformers, because the membrane does not allow the release of produced gases to air.

According to IEC interpretation [2] of DGA, the assumed initial transformer failure is diagnosed primarily on the basis of the given hydrogen to hydrocarbon ratios. CO and CO_2 are auxiliary indicators for the condition of cellulose insulation, and the CO_2/CO ratios between 3 and 10 are considered to be typical for normal cellulose degradation.

IEC 60599, Table A2 specifies the range of 90% typical CO and CO_2 concentration values observed in power transformers, from about 25 electrical networks worldwide and including more than 20000 transformers. Typical values apply to both open-breathing and hermetically sealed (close-type) transformers. Typical concentrations should be primarily considered as initial guidelines for diagnosis of transformer condition when no other experience is available.

It is recommended that the 90% typical values should be used only for orientation, in the case if there are no data of one's own.

Permanently increased concentrations of CO and CO_2, although not accompanied by increased contents of other gaseous products of oil degradation, can cause concern to transformer users, because they interpret such data solely as a result of accelerated cellulose degradation – what means a shortening of transformer life.

The condition of 26 closed-type power transformers installed in Croatia, with 1-10 years of service without any registered stress or fault inception ("healthy transformers") was investigated.

Laboratory tests were carried out to determine the impact of materials (oil and paper) as well content of residual air on the development of CO and CO_2 gases in closed-type power transformers.

2. FORMATION OF CO AND CO_2

Gases are the first products of the insulating oil and paper materials (cellulose) degradation in normal aging of insulating system as well as in rapid degradation due to increased electrical and thermal stresses.

Mineral insulating oils are made of a blend of different hydrocarbon molecules containing CH_3, CH_2 and CH chemical groups linked together by carbon-carbon molecular bonds. Scission of some of the C-H and C-C bonds may occur as a result of electrical and thermal faults, with the formation of small unstable fragments, in radical or ionic forms which recombine, through complex reactions, into gas molecules such as hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO) and carbon dioxide (CO_2). Formed gases dissolve in oil and distribute throughout the oil volume by circulation and diffusion.

Solid insulation in electrical equipment is largely made of cellulose in the form of electrotechnical paper (Kraft paper) and pressboard. The polymeric chains of solid cellulosic insulation contains a large number of anhydroglucose rings, and week C-O molecular bonds and glycosidic bonds which are thermally less stable than the hydrocarbon bonds in mineral oil, and which decompose at lower temperatures. Significant polymer chain scission occurs at temperatures higher than 105 °C, with complete decomposition and carbonization above 300 °C. Carbon monoxide and dioxide as well as water are the final products of cellulose degradation. Furanic compounds are intermediary products of cellulose degradation, they can be analysed according to IEC 61198 [3] and used to confirm cellulose degradation.

In individual power transformers, CO and CO_2 concentrations can be permanently or temporarily increased depending on various possible parameters:

- influence of design (air- breathing or closed–type transformers, mass ratio oil/cellulose, winding design, cooling system),
- influence of mineral oil and solid insulation quality,
- influence of processing (bad removal of moisture and oxygen in factory, moisture ingress at surface of oil immersed cellulose during assembling of bushings, absorption of air during shipment and bad removal during evacuation in the field due to "oil corks" which do not dissolve at low temperatures),
- influence of transformer loading (operating temperatures)

It is important to take into account all these variables when determining the origin and cause of content increase of these gases.

The rate of CO and CO_2 generation is exponentially dependent on temperature, and directly on volume of the material.

3. CLOSED-TYPE POWER TRANSFORMERS INSTALLED IN CROATIA

Analysis of the condition of 26 closed-type power transformers installed in Croatia was made and presented separately for 5 closed-type generator transformers and 21 closed-type transmission transformers.

3.1. Generator transformers

These 5 generator transformers are located in Hydro Plants, in service from 5 to 10 years, and normally run at 100 % load except when the power station is shut down. The results of the latest dissolved gas analysis for closed-type generator transformers are shown in the table I.

Table I - Gas values, μL/L (ppm) and ratio CO_2/CO for generator transformers

GAS, μL/L (ppm)	Rate of transformer / Type of cooling / Year of service				
	1. 245 kV OFAF 2007.	2. 123 kV ONAF 2006.	3. 123 kV ONAF 2004.	4. 123 kV ONAF 2004.	5. 123 kV ONAF 2000.
Hydrogen, H_2	6	6	3	3	3
Methane, CH_4	15	11	10	10	10
Acetylene, C_2H_2	0	0	0	0	0
Ethylene, C_2H_4	1	0	0	0	0
Ethane, C_2H_6	2	0	0	0	0
CO	824	1307	716	1046	871
CO_2	1637	2942	3462	3422	3878
Ratio CO_2/CO	2.0	2.2	4.8	3.2	4.4
Oxygen	9592	12581	5808	6497	5359
Nitrogen	45365	69544	28573	35817	25427

Graphical presentation of the CO gas formation in closed-type generator transformers during their normal operation is given in figure 1.

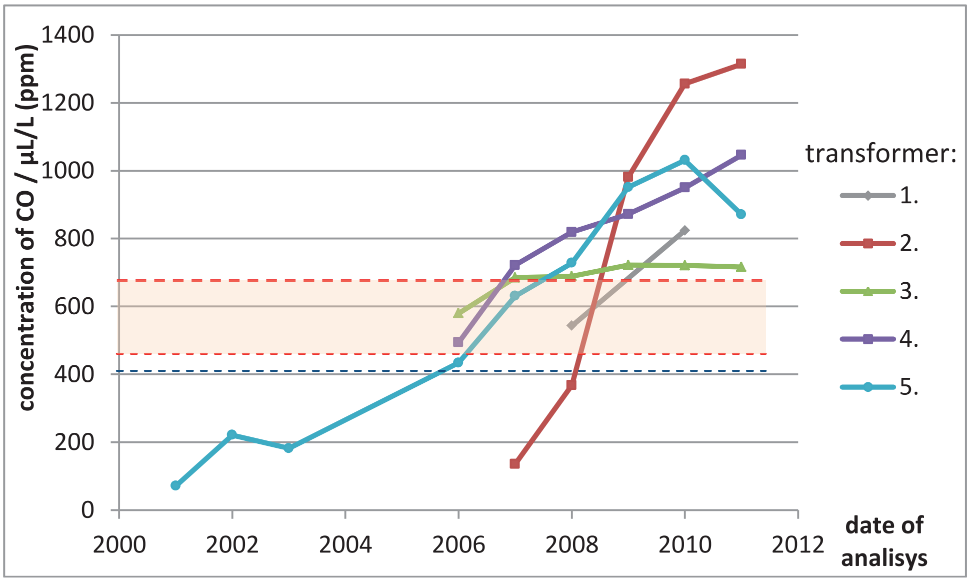

Figure 1 - Formation of CO in closed-type generator transformers

In all five generator transformers, already after 1-4 years of operation, CO gas concentration is significantly higher than the range of normal values given in IEC 60599 Tbl. A2 (400 - 600 μL/L) and the normal values according the IEEE Std C57.104 Tbl. 1 (350 μL/L).

Graphical presentation of the CO_2 gas formation in closed-type generator transformers during their normal operation is given in figure 2.

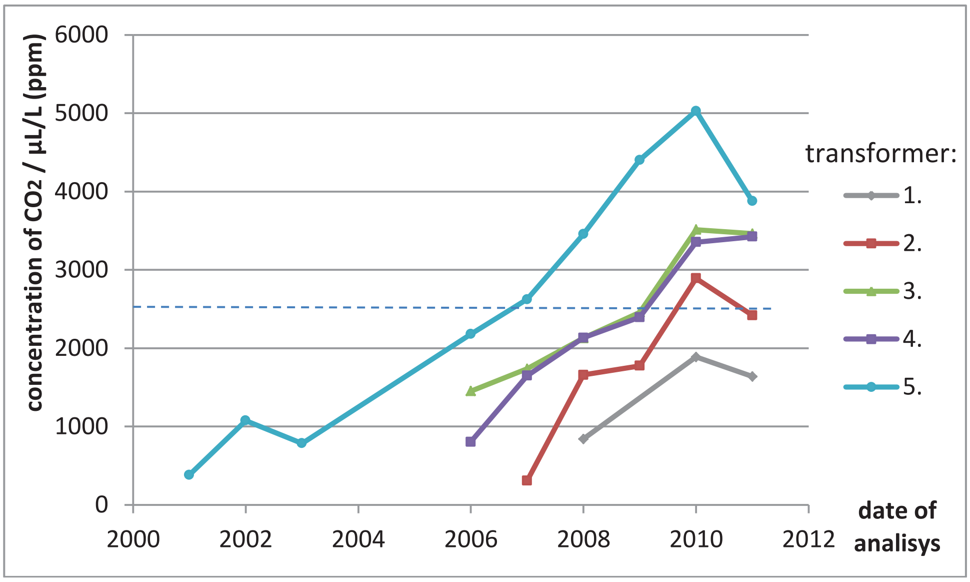

Figure 2 - Formation of CO_2 in closed-type generator transformers

At all generator transformers the value of CO_2 concentration is within the normal range according to IEC 60599 Tbl. A2 (3800 -14 000 μL/L), while the normal value of CO_2 by the IEEE Std C57.104 Tbl. 1 (2500 μL/L) is exceeded after approximately 5 years of normal operation.

The measured water content in the oil for all generator transformers is lower than 10 mg/kg.

3.2. Closed–type transmission transformers

These 21 closed-type transmission transformers are in operation from 1-10 years and normally loaded. The range of characteristic gas values, μL/L (ppm) and ratio CO_2/CO for transmission power transformers are shown in the table II.

Table II - Range of gas values, μL/L (ppm) and ratio CO_2/CO for transmission power transformers

GAS, μL/L (ppm)	Rate of transformer/ Type of cooling / number of units				
	20 MVA 110 kV ONAN/ONAF 7 units	40 MVA 110 kV ONAF, ONAN 6 units	63 MVA 110 kV ONAF 2 units	100 MVA 110 kV ONAF 1 unit	≥300 MVA 420 kV OFAF 5 units
Hydrogen, H_2	5-20	11-18	12-17	16	2-31
Methane, CH_4	2-8	7-12	11-14	22	10-18
Acetylene, C_2H_2	0	0	0	0	0
Ethylene, C_2H_4	0	0	0	1	0-1
Ethane, C_2H_6	0	0	0	3	0-3
CO	148-1197	761-1457	1135-1157	1208	468-825
CO_2	337-2853	1274-4652	2270-2521	2817	1945-2892
Ratio CO_2/CO	1,0-11,2	1,7-3,6	2,0-2,2	2,3	2,5-4,9
Oxygen	7117-19444	5532-10794	9706-10582	7857	5642-11384
Nitrogen	31850-63613	27110-55101	52276-60703	50629	24404-58148

The measured water content in the oil for all transmission transformers is lower than 10 mg/kg.

According to IEC 60599, the ratio CO_2/CO < 3 indicates a possible accelerated degradation of cellulose. In closed-type transformers, due to lack of oxygen, the thermodynamic balance is shifted towards generation of CO, so a lower ratio CO_2/CO is frequently found.

For 15 closed-type transmission power transformers (with OLTC) the ratio CO_2/CO is lower than 3, and 1 of the 21 transformers has ratio higher than 10. Only at 5 of them typical CO_2/CO ratios are between 3 and 10 which coresponds to normal degradation of cellulose.

Accelerated degradation of cellulose can be confirmed by increase of furan content in oil. Furan content in oil was analysed in the all closed-type transmission transformers. It was found to be low, what means that there are no indications of accelerated cellulose degradation.

4. LABORATORY TESTINGS

Laboratory tests were carried out to investigate the impact of the main isolation materials oil and paper, as well as the residual air in oil, on formation of CO and CO_2 gases.

4.1. Influence of oil and paper on CO and CO_2 formation

Kraft paper and pressboard were subjected to thermal degradation testing in an oven at 115 °C. All samples were tested separately, in degassed inhibited mineral oil (total gas content between 1.5% and 2.0%). Residual oxygen content was 4000-4500 µL/L, CO < 5 µL/L and CO_2 65 – 75 µL/L. Kraft paper and pressboard to mineral oil ratio was 1 g in 50 mL of oil. Tests were performed in gas tight syringes.

As expected, thermal degradation of mineral oil and Kraft paper resulted in significant increase of CO concentration.

Gassing of mineral oil at higher temperatures is well known and it has been shown that different mineral oils can generate different amounts of CO and CO_2 [5].

CO generation from mineral oil and Kraft paper was linear through the testing period and it was more intensive from Kraft paper.

CO generation from pressboard was significant after 48 hours of testing, but it did not increase during testing period. After 360 hours, the pressboard had minor influence on CO generation. Influence of mineral oil, Kraft paper and pressboard on CO generation is presented in figure 3.

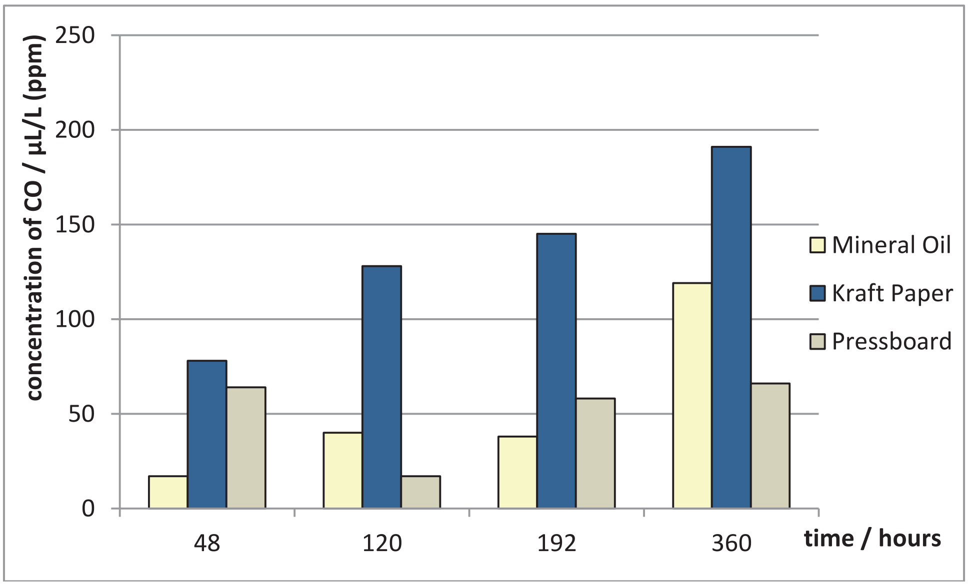

Figure 3 - CO generation from mineral oil, Kraft paper and pressboard at 115 °C

Kraft paper, as well as pressboard, had the similar impact on the generation of CO_2. The impact of mineral oil is insignificant, as shown in figure 4. The CO_2 gas amount generated from Pressboard decreased after 360 hours of testing (possible gas leaking from syringes).

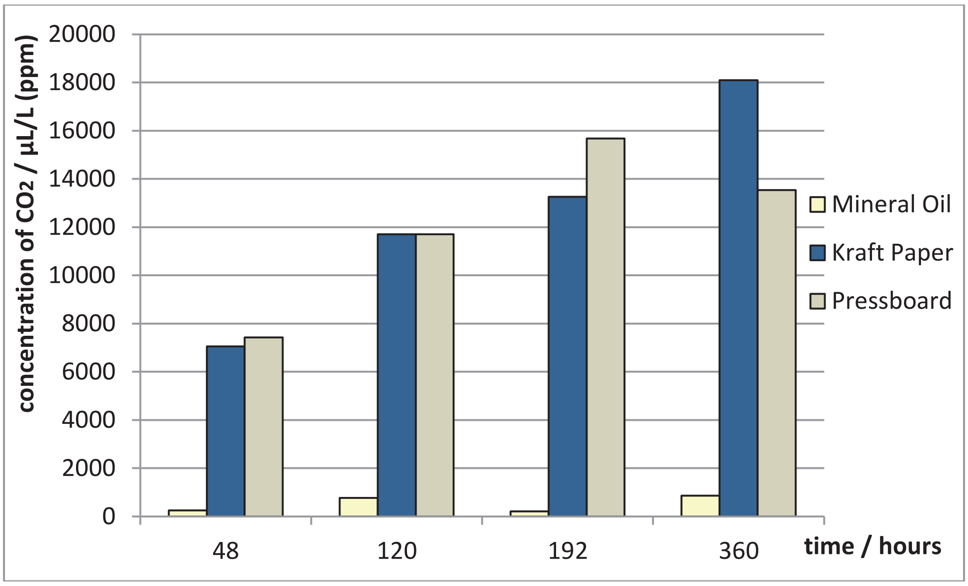

Figure 4 - CO_2 generation from mineral oil, Kraft paper and pressboard at 115 °C

4.2. Influence of residual air on CO and CO_2 formation

The impact of oil degassing on CO and CO_2 formation was investigated. New degassed mineral oils with different total content of residual air in the oil (0.5%, 1.5% and 2.0%), were subjected to thermal degradation testing in a oven at 70°C. The development of emissions of CO and CO_2, after 168 and 336 hours of test, was monitored.

As presented in figure 5. oil with more residual air (2.0% TGC) had higher impact on concentrations of CO and CO_2 than oil with less residual air (0.5% TGC).

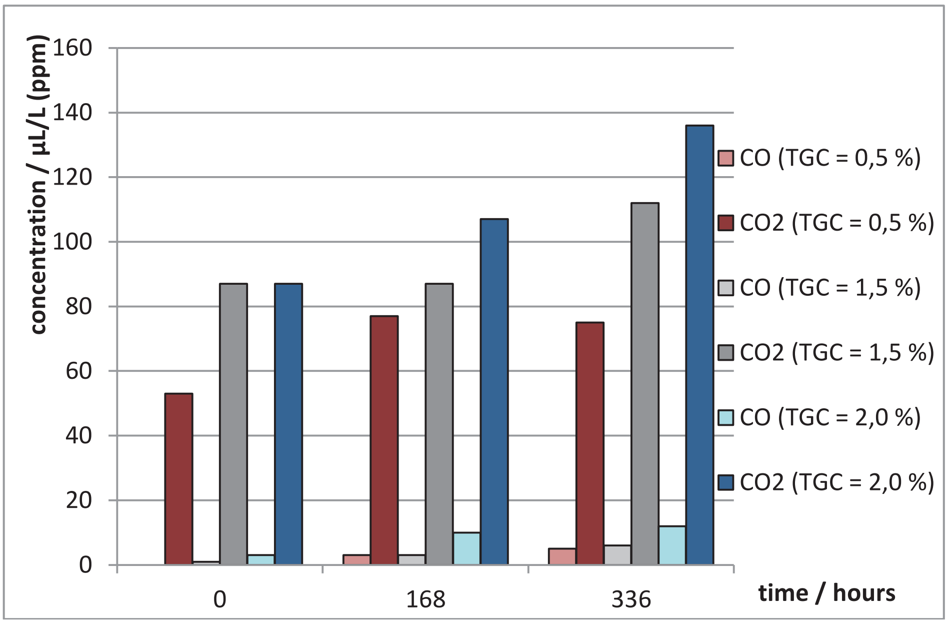

Figure 5 - Influence of total gas content (TGC) on formation of CO and CO_2 at 70 °C

It is important to degas the oil and transformer during the manufacturing process of transformer to the lowest possible amount of residual gas. The total content of gas in oil in closed-type transformers should be kept low during the operation, and if it is higher than 5% it is necessary to degas the oil, to prevent the increased development of CO.

5. CONCLUSION

Carbon monoxide and dioxide as well as water are the final products of cellulose degradation. Except cellulose, and in lesser extent mineral oil, the auxiliary materials (paints, rubber, plastic materials, glues etc.) also have the impact on CO and CO_2 generation.

Laboratory testing show the influence of residual air (total gas content) in oil on formation of CO and CO_2. Better degassing assures lower concentrations of these two gases. In transformers with closed-type breathing system oxygen content in oil is lower than in air saturated oil, so the equilibrium is shifted towards CO production. Besides that, the membrane does not allow the release of produced gases to air, so increase of the gases during operation is higher.

Because of presented facts it can be concluded that in normal operating closed-type transformers, CO can be present in greater concentration and CO_2 in some lower concentration than in transformers with open breathing system (lower ratio CO_2/CO).

It is important to distinguish the normal values for CO and CO_2 concentration for closed-type and open breathing system transformers. The typical values for CO as well scheme concerning their ratios need to be revised in standard IEC 60599. The criteria need to be established separately for closed type transformers as particular category of equipment.

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